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A TRANSPORTABLE PHOTOVOLTAIC ARRAY FOR TEMPORARY FIELD CAMPS

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A TRANSPORTABLE PHOTOVOLTAIC ARRAY FOR TEMPORARY FIELD CAMPS

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Résumé

Aucune problème technique majeur s'oppose à l'utilisation de systèmes photovoltaïques pour produire l'électricité dans les camps temporaires des régions arctiques et subarctiques. Les modules photovoltaïques fonctionnent bien lorsqu'il fait froid. L'énergie solaire est disponible en quantité suffisante dans le Nord durant la période où les camps sont en pleine opération, c'est-à-dire du mois d'avril au mois de septembre. D'autres raisons bien précises empêchent leur utilisation, notamment le fait que les systèmes photovoltaïques soient habituellement conçus comme une structure permanente alors que les camps revêtent souvent un caratère saisonnier. Ce document rapporte le travail de l'entreprise AstroPower Canada dans le but de concevoir une installation photovoltaïque adaptée à une utilisation temporaire dans le Grand Nord canadien.

AstroPower a élaboré et mis à l'essai deux structures adaptées aux situations temporaires, dans le Nord canadien ou ailleurs, et comprenant un système pourvu d'un mécanisme permettant de suivre la position du soleil. Les deux structures répondaient pour l'essentiel aux objectifs de conception établis pour le projet. Comme les deux montages n'ont été réalisés qu'à titre de prototype aux fins de ce projet, certains travaux de finition doivent être achevés.

L'un des modules est particulièrement bien adapté à une installation temporaire, qui ne nécessite qu'un faible apport en électricité. L'autre module convient mieux à une installation qui demeure en place pour une période de deux semaines ou plus mais il peut fournir beaucoup plus d'électricité.

Un mécanisme à bascule sur axe horizontal orienté est-ouest, permettant de suivre la position du soleil, peut produire de l'électricité de façon efficace au nord de cercle polaire. Plus au sud, les bénéfices découlant d'une telle installation ne justifient pas les coûts.

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A Transportable Photovoltaic Array for Temporary Field Camps

1. Introduction

There are no significant technical problems which would limit the use of PV power systems at field camps in our arctic and subarctic regions. Photovoltaic modules work well in cold weather, and there is plenty of solar energy available in the North during the months when field camps are operating (typically April through September). However, there are specific barriers to the use of PV power systems in northern field camps, one of which is that PV systems are normally designed to be permanent structures, whereas arctic camps are often seasonal. This document reports on AstroPower Canada's efforts to design a photovoltaic (PV) array which is suitable for use in temporary field camps in northern Canada.

Typically, a PV power system is designed to operate for 20 years. Thus the array support structure is designed as a permanent fixture, and little consideration is given to the ease with which the structure can be installed; it is assumed that it will be done only once, and that trained craftsmen (or a hobbyist/handyman with plenty of time) will be doing the bulk of the work. In contrast, field camps in the north are almost always temporary (even those few sites with peramanent buildings typically operate for less than half of each year), and the cost of keeping men in the North means that available manpower is severely limited. As a result of these restrictions, the design goals we developed at the beginning of this project (Table 1) reflect a strong emphasis on keeping the structure easy to assemble and disassemble, even in cold weather, and easy to transport. Even the goal of developing a suitable tracking array was merely an attempt to make the overall system smaller by replacing some bulky PV modules (and support structure) with more compact control circuitry, while maintaining the same net output of the array.

AstroPower Canada Ltd., 1990

Table 1: Project Design Goals

1) The set up time (beginning with unloading the array from the transport vehicle to having a fully secured and functional PV array) should not exceed 4 hours for 2 persons dressed in heavy winter clothing. Similarly, the same limit should apply to the time required to take down, pack and load the array.

2) The PV array must be designed such that it can be readily transported by both a Twin Otter and a Bell 206L helicopter. In addition to the size and shape restrictions this implies, we are assuming that the weight of the array should not exceed 0.25 kg per peak watt (e.g. a 200 Wp array should weigh not more than 50 kg), thus allowing a moderate size, complete power system to be transported in one trip. (As a reference, our standard construction modules weigh 0.14 kg per peak watt, without a support structure and wiring.)

3) The cost of a transportable, fixed tilt array (mounting structure, PV modules, electrical and mechanical hardware) should not exceed twice that of an equivalent number of standard PV modules alone. (As a reference, the cost of a fixed tilt array is typically 1.25 - 1.5 times the cost of the modules alone, excluding installation costs.)

4) The cost premium of an automatically tracking transportable array over a fixed tilt, transportable array should not exceed 80% of the benefit in terms of additional electrical output (e.g. if automatic "flipover" tracking increases an array's output by 30%, then the cost premium of an automatic tracking array should not exceed 24%). Achievement of this goal will ensure that a tracking array costs less than a fixed array, when based on equal amounts of energy output, thus offsetting any possible concern of decreased reliability of the tracking array.

5) Because we fear that any packaging material would be lost or destroyed during the period when the field camp is in operation, our design goal is to integrate all packaging elements into the array design such that they are permanently fixed to it, even in the deployed position.

6) Although durability is not as great a concern for transportable systems as for fixed systems, our goal is to design the array for a 10 year life (approximately half of the design life of permanent PV arrays), including 5 setup, take down and transport cycles per year.

2. Weather Data Analysis

A substantial part of this project was invested in determining the actual output of a PV array in various parts of the arctic, during different seasons. This work was limited to computer analysis of recorded weather data; field measurements of solar data have been carried out by the Atmospheric Environment Service of Environment Canada for many years, so there was little need to supplement this data at this stage. During this phase of the work, we looked at the potential for both fixed arrays and tracking arrays.

AstroPower purchased detailed weather data for 1986 for seven arctic sites from Environment Canada, then hired the Watsun Simulation Laboratory at the University of Waterloo to employ their sky modelling program to provide us with data in a format which we could readily use for further analysis. The content of this data is described in figure 1.

Sites	Reslolute, NWT Whitehorse, Yukon Inuvik, NWT Yellowknife, NWT, Alert, NWT Iqaliut, NWT Hall Beach, NWT
Year	1986
Resolution	Hourly
Surfaces	13 surfaces, from 90° south facing, through horizontal, to 90° north facing, at 15° tilt increments. "Perfect" flipover tracking surface (i.e. a moving surface which is mounted on a single east-west axis mounted parallel to the ground and which follows the sun. 2-axis tracking surface which perfectly follows the sun, always remaining normal to the direct beam solar radiation.
Other Data	Ambient temperature, relative humidity, wind speed.

Figure 1: Description of Weather Data

The results of the analysis are reported below; for those who wish more detail a summary of our weather data is included in Appendix A.

2.1 Fixed Tilt Arrays

Analysis of the weather data for fixed tilt arrays is relatively straight forward. As this project is concerned primarily with temporary field camps, we chose the optimum south facing angle for each site, for each month. Both the tilt angle and average peak sun hours per day for each month are recorded in table 2. (Please note that this data forms the baseline for comparison of the tracking systems considered elsewhere in this report.)

While we anticipate that changing the tilt angle once each month on any array structure designed for use in a temporary field camp will be a minor task, our data shows that this will not be necessary at any of the seven sites studied. In fact, there is a single tilt angle which the array can be set to during the summer (May through August) which yields the maximum output. While this is not obvious from table 2, it is a result of the fact that the maximum reported there is only insignificantly higher than the next best angle (refer to the data in appendix A). As it turns out, the optimum summer tilt angle for all sites except Alert is 30° from horizontal; at Alert it is 45°. If the operating season extends outside of the May though August period, monthly adjustments of the tilt angle would normally be beneficial.

2.2 Tracking Arrays

In looking at a simple tracking mechanism, it was our hope that a simple tracking array could be developed which would operate effectively in the North, taking advantage of the long hours of sunlight, and would result in a net reduction in the bulk of a PV array. Because our array design had to be transportable, complex tracking mechanisms were ruled out as unsuitable; even if they were not costly, the structure required would almost certainly be fairly bulky, and the precision needed to set it up properly in a field camp would almost certainly be greater than desired. Thus the only tracking format which we considered designing was a simple array which rotated about a single east-west axis which was parallel to the ground. We termed this concept "flipover" tracking, which we further divided into three categories:

i) 2-station tracking, in which the array is limited to only two positions or stations. Station 1 is south-facing, and station 2 is north-facing. In our analysis, the tilt angle of each of these stations would be adjusted on a monthly basis, when this improved performance.

Table 2: Solar Availability on Fixed Surfaces

Monthly Average Solar Energy Available on an Optimally Tilted South-Facing Surface (peak sun hours/day).

MONTH	Resolute 74.7°N		Alert 82.5°N		Whitehorse 60.7°N		Iqaliut 63.8°N		Inuvik 68.3°N		Hall Beach 68.5°N		Yellowknife 62.5°N	
January	na		0.0	na	0.0	60	0.6	75	1.4	75	0.3	75	0.1	60	1.3
February	75		0.8	na	0.0	60	4.1	60	2.9	60	1.4	60	2.6	60	3.5
March	60		5.5	60	2.5	45	3.5	45	7.1	60	5.6	60	5.9	45	5.2
April	45		8.1	60	7.6	30	5.3	30	7.0	45	7.3	45	8.2	30	7.9
May	30		6.7	45	7.1	15	5.3	15	6.1	30	5.6	30	6.3	15	5.9
June	30		6.0	0	5.6	0	6.3	0	5.6	15	7.3	15	6.9	0	6.2
July	15		4.4	30	4.7	0	5.6	15	5.7	15	5.1	15	5.5	15	6.7
August	15		2.3	45	3.9	15	4.4	15	3.1	15	3.8	30	3.6	15	4.7
September	45		2.8	60	2.4	30	4.0	30	2.5	45	3.6	45	2.1	45	3.9
October	60		2.0	75	0.4	45	1.9	60	3.0	60	1.3	60	2.5	45	1.7
November	na		0.0	na	0.0	60	1.2	60	1.1	75	0.8	75	0.6	60	1.8
December	na		0.0	na	0.0	60	0.6	75	0.7	na	0.0	na	0.0	75	0.7

The first number in each double column is the tilt angle (degrees from horizontal) for the optimum output, with the second being the solar energy available, in peak sun hours per day.

Note that the June entry for Alert indicates that horizontal surface is optimum; all other entries are for south-facing surfaces.

ii) **3-station** tracking, which is similar to the 2 station tracker, except that a third station is added between the first two, at or near horizontal.

iii) **Continuous** tracking, where the array is constantly undergoing minor tilt adjustments such that it is always directed toward that part of the sky which is brightest.

As a reference point, solar availablility for a standard 2-axis tracking system which perfectly follows the sun was also calculated, but a design of this type was not considered. Existing designs for this type of tracker are usually limited to a total movement of less than 180°, and thus will not operate properly in

the arctic where continuous tracking around the horizon would be necessary. As well, the complexity of the movement was a concern in an environment which can be very hard on exposed equipment.

Figures 2 and 3 show the potential benefit of 2-station and 3-station tracking for each month at four of the sites we studied. At the other three sites (Whitehorse, Yellowknife and Iqaliut), the potential benefit from tracking was negligible, being under 5% even for the single best month at each site.

In order to analyse the weather data properly for these two figures, we proposed a "real" tracking control scheme. We chose a relatively simple but realistic one, whereby the array would move to a new position only if the irradiance at the new position was at least 10% greater than the irradiance at the current position. In addition, the array would always stay in the current position if the irradiance level of all stations was below 75 W/m^2. This control algorithm is simple enough to implement in control electronics, and should ensure that energy is not wasted by having the array move frequently, seeking marginal increases in irradiance which yield no detectable net gain. The effect of introducing this control algorithm is to lower the amount of insolation available as compared to a "perfect" control algorithm for a 2-station

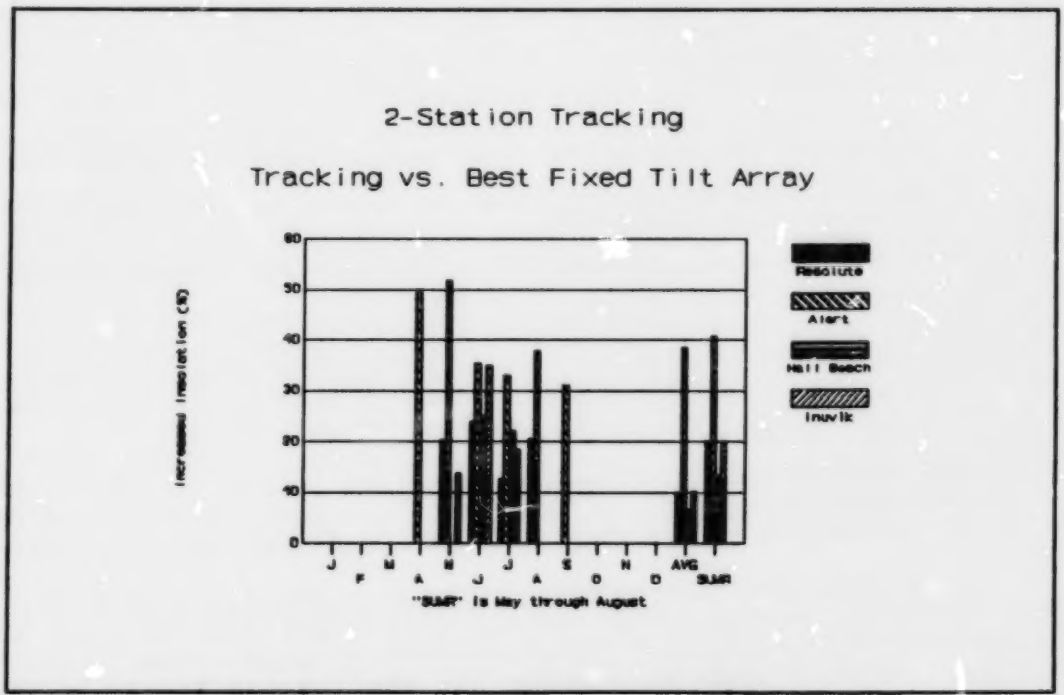

Figure 2: 2-Station Tracking Characteristics

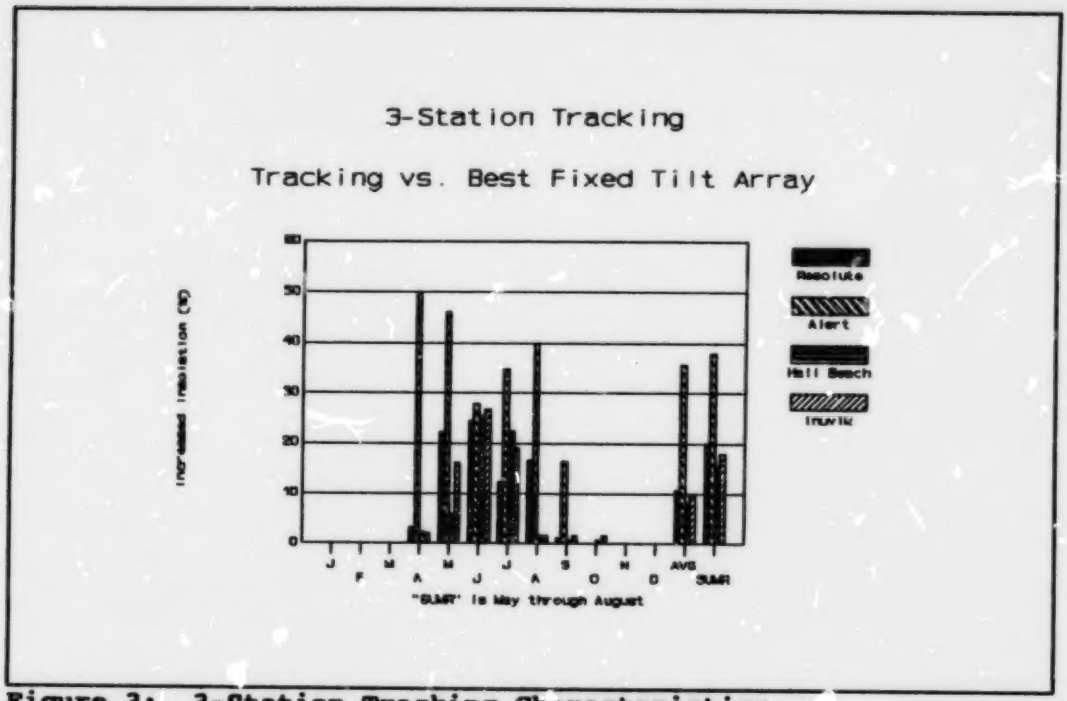

Figure 3: 3-Station Tracking Characteristics

tracker. (Another feature which should be included in a tracking control algorithm is a time delay or averaging feature which ensures that the array tracking mechanism is not activated by short term phenomena such as reflections from passing clouds or nearby personnel. This feature can be ignored when conducting our weather analysis; our data comes only in hourly time increments, thus momentary disturbances are missing.)

Both solar energy availability and the staffing of arctic field camps are highly seasonal, with each being high in the summer; for this reason much of our analysis was restricted to the summer months only, which we defined as May through August. Figure 4 is a comparison of the effectiveness of various tracking concepts. The baseline data (0%) corresponds to the insolation on the best fixed angle. The maximum (100%) corresponds to the insolation on a perfect 2-axis tracking surface (as calculated by Watsun). Thus the two plotted curves show where the ideal and 2-station flipover tracking fall between these two curves. Note that for three of the four sites where tracking gives a significant benefit (Resolute, Alert and Inuvik; refer back to figure 2), the 2-station tracking produces almost as much benefit as the ideal, continuous, flipover tracking. Hence we can conclude that these two stations are sufficient, and that there is little benefit in adding a third station, or going to a continuously adjustable

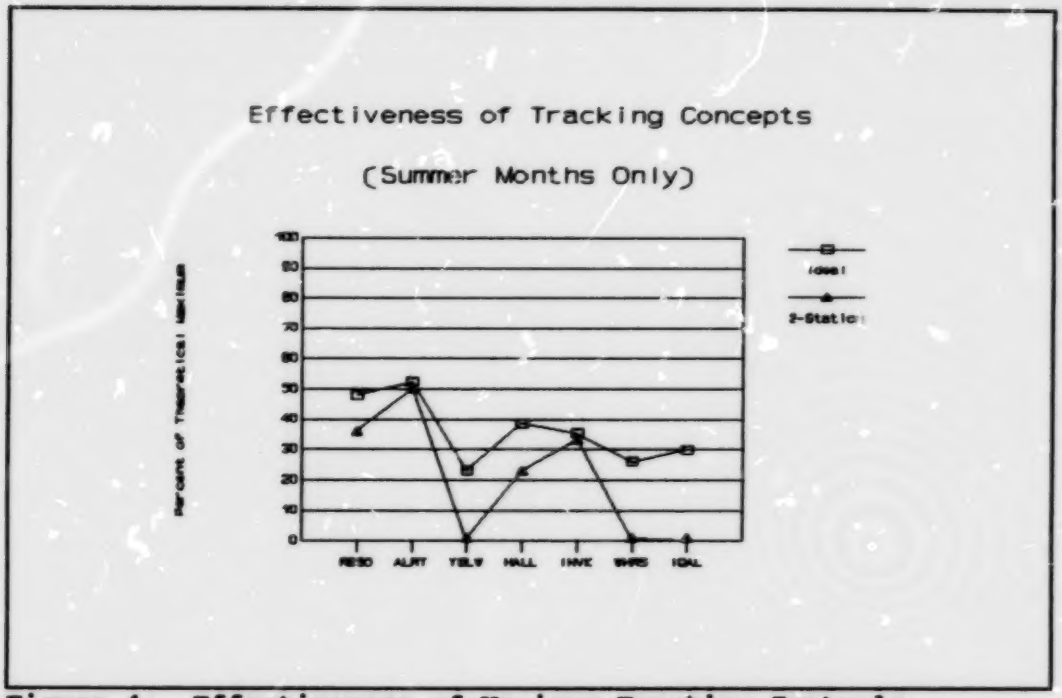

Figure 4: Effectiveness of Various Tracking Controls

array, unless they are simpler to implement.

One thing that figures 2, 3 and 4 indicate is that there are some sites where flipover tracking produces a greater benefit than others. Not surprisingly, the biggest factor in determining the effectiveness of flipover tracking appears to be the site latitude. The further north, the greater the benefit of this type of tracking. In figure 5 we have plotted the potential benefit of tracking vs. the site latitude, based on 3-station data from the summer months. This graph clearly shows the strong dependence upon latitude, and further indicates that flipover tracking is probably rarely worth the cost for sites below the arctic circle (66.7°N).

3. Solar Trackers

We started our tracker development with the understanding that we would only consider rotating the array about a single, horizontal, east-west axis. There were several reasons for limiting the study to this:

1. Achieving high reliability and durability of moving parts in the harsh arctic environment is not easy, thus we decided to limit our work to single axis units only.

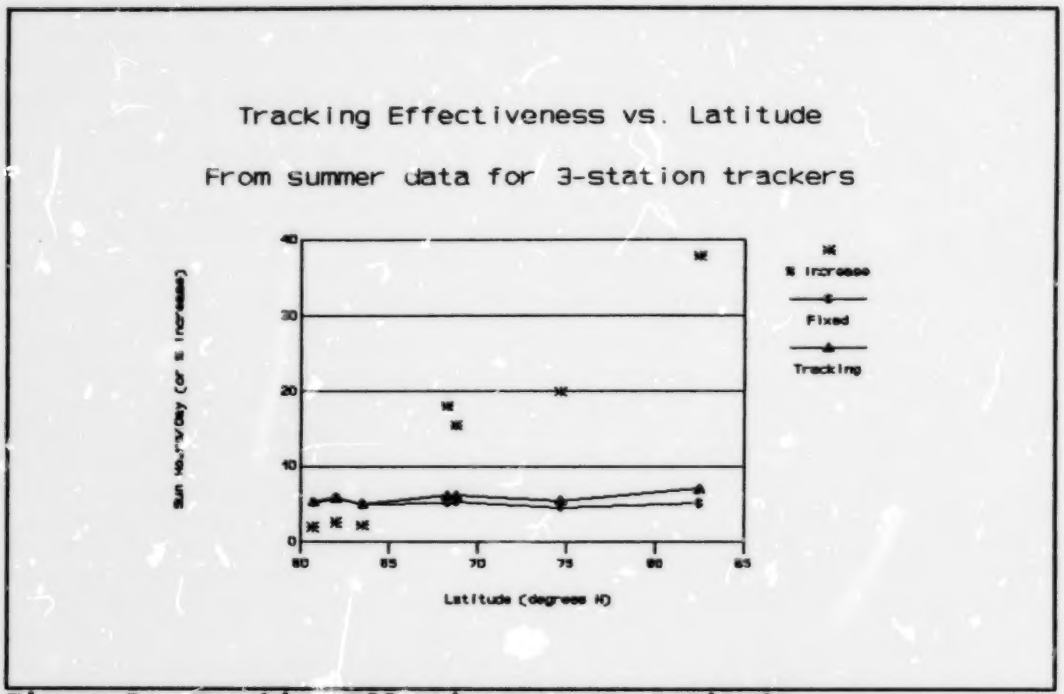

Figure 5: Tracking Effectiveness vs. Latitude

The two solid lines are in peak sun hours/day. The asterisks indicate the percent difference between these two lines.

2. Keeping the axis horizontal allowed us to keep the entire structure close to the ground, reducing the bulk of the structure when transported, and making assembly and disassembly easier. The low profile of this type of structure also affords some protection from the occasionally harsh arctic winds.

3. Using an east-west axis allows for a "primary" array position facing south at a high tilt angle, the same orientation which would be used for a fixed tilt array. This is important not only because it is important to have the array oriented as directly as possible at the sun during midday - when the energy available is greatest - but it also allows the field user to manually place the array in this position, and leave it, should the tracking mechanism fail.

Given this limitation on the actual tracking motion, there are three basic methods of "detecting" the brightest area of the sky, to which the array should be pointed.

One method of detecting the brightest area in the sky is to use a clock, which "knows" where the sun is, and assumes this to

be the brightest area of the sky. This technique suffers in cloudy weather, when the location of the sun may not identify the brightest area in the sky, and when the array may needlessly consume energy tracking the sun even when no signifcant amounts of energy are available in any direction. However the most serious problem with this technique is the potential for the clock (or the array mechanics) to be set incorrectly, resulting in the array tracking an area of the sky where the sun is not. This risk, present in any clock-based tracker, was considered to be even greater in an array which was intended to be moved from place to place.

A second method of detecting the brightest area of the sky is to place two or more irradiance sensors in separate, fixed positions. Control logic is then provided to move the array into alignment with the sensor which has the highest output. Because of the number of sensors needed, and the logic required to sort through them, this technique becomes unwieldy if too many possible array positions are included. However, for the simple, single-axis tracker with only 2 or 3 possible positions that we were considering, this technique is reasonable. In fact, one of the tracking controllers we chose to prototype is based on this principal; benefits and problems of this method are further discussed in terms of the actual prototype we built (see section 3.1.1). One general limitation that applies to this type of tracking controller is that it selects the orientation for maximum irradiance only from a small number of predefined positions. If the true direction of maximum irradiance is between positions, this will not be detected, and the array will only end up "near" this ideal orientation.

The third basic method of detecting the area of maximum solar irradiance is to incorporate irradiance sensors which move with the array, arranged at various angles such that they indicate in which direction the brightest area is located. Logic is used to move the array in the direction indicated; the movement normally is stopped when the sensors are "balanced", indicating that a maximum in brightness is located in the direction which the array is now facing. The major problem of this technique is related to the way in which the stopping point is determined. Normally the array will stop when two sensors are balanced. While this can indicate a bright area, it may also indicate a position where the irradiance is equally low in both directions. Thus this type of tracker is prone to getting "lost". We also chose to prototype a tracker based on this technique (see section 3.1.2).

Naturally, these three basic techniques can be added too with various control logic, and can also be combined.

3.1 Prototype Designs

As indicated, we designed and prototyped trackers based on the second and third basic techniques discussed above; the actual designs and characteristics of each are discussed below. The clock based tracking technique had one obvious advantage for use in the North - it was not based on external sensors, and could be more readily protected from the environment. However, we chose not to prototype one of these units for economic reasons - we could neither purchase nor build a suitable "clock" at a cost low enough to make a marketable tracker. There were some other reasons why this type of tracker was rejected, notably because the controller would, in fact, require external sensors to provide feedback as to the present position of the array, and because of perceived difficulties in keeping the clock set properly. This latter can be a particular challenge in northern Canada, where the time zones begin to converge, such that the standard time can vary from solar time by two or more hours.

3.1.1 Two-Station Tracking Controller

The schematic of the control electronics for the two-station prototype tracker is shown in figure 6. We limited this to a 2-station system to simplify the logic; it is much simpler to select the best of two positions than the best of three (or more). Even so we feel that one of the major drawbacks of this controller is its complexity, which leads to high costs and questionable reliability.

Physically, the controller consisted of a small box housing the circuit board, two identical sensors consisting of a single solar cell mounted at the outer ends of two arms. Limit switches, activated by a cam attached to the rotating axis, to indicate that the array had reached position were also located on these arms. A dc motor with a built-in gear head was used to drive the array.

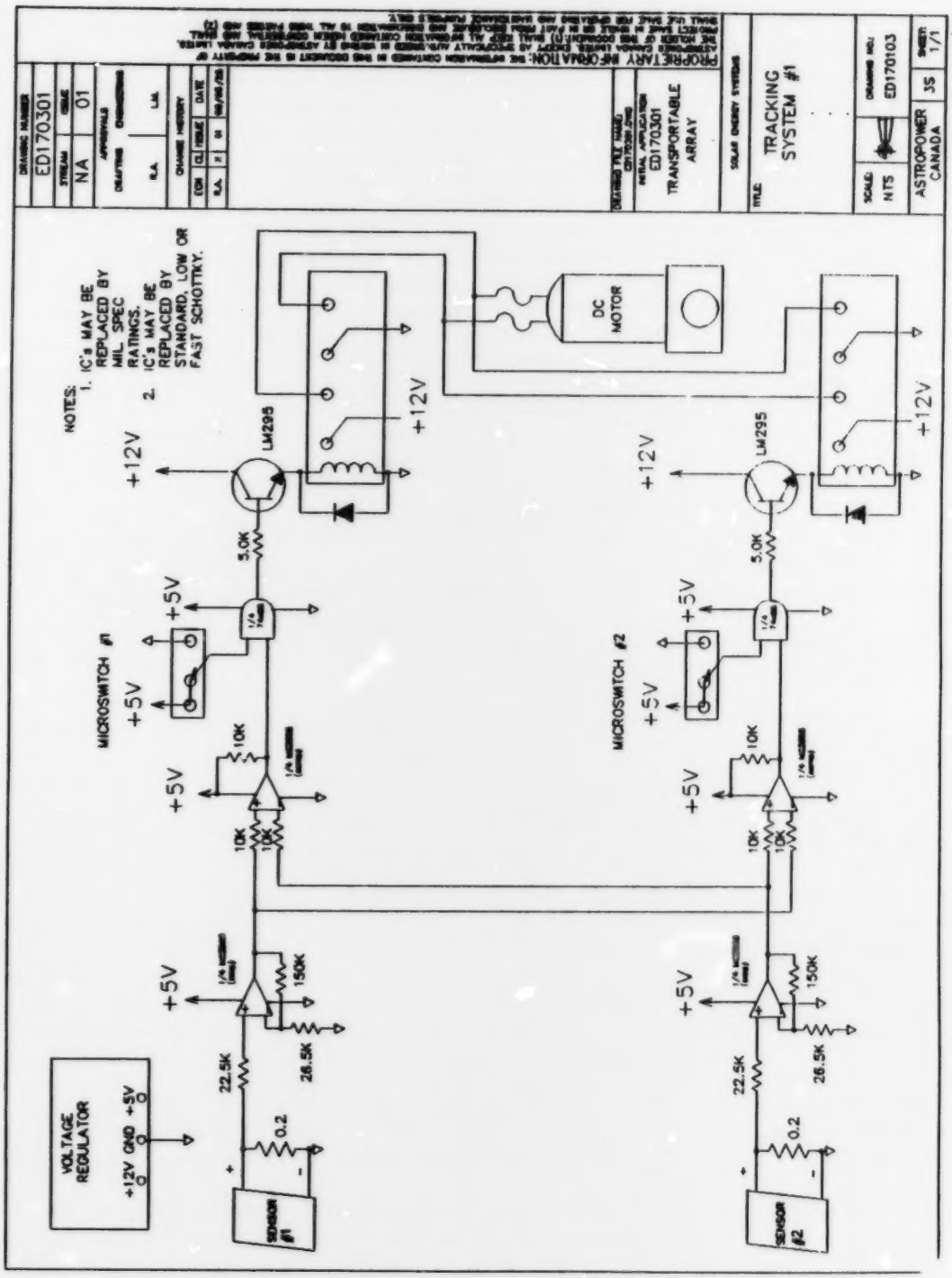

Figure 6: Control Circuit for 2-Station Tracker

This controller worked well in controlled tests, taking approximately 9 seconds to move from one position to the other. With a power draw of 20 watts, the motor consumed approximately 0.05 Wh per move. The number of moves is site and weather dependent, but our analysis showed that the average number of moves per day would be 1.5, yielding a typical energy consumption for the motor of 0.08 Wh/day. Added to this would be the energy consumption of the control electronics, which was measured at 0.86 watts, or 20.6 Wh/day. It is readily apparent that over 99% of the parasitic energy losses of this tracking system are a result of the control electronics, not the drive motor. Even so, the total parasitic energy losses amount to less than 10% of the daily output of a single, fixed PV module. This parasitic energy loss would need to be subtracted from the gross tracking benefit in order to determine the net benefit of the tracking.

Example calculation of net tracking benefit:

Number of modules in array: 6

Daily charge to battery for fixed array: 175 Wh/module

Gross tracking benefit: 20%, or 35 Wh/module

Daily parasitic losses: 20.7 Wh

Net tracking benefit: (6x35)-20.7 = 189.3 Wh/day, or 18%

3.1.2 Direct Drive Tracking Controller

The direct drive tracking controller we prototyped was extremely simple. The circuit is shown in figure 7. This tracker used the power from two small sensor panels to directly power the drive motor, thus avoiding any power drain on the main system batteries. The two sensor panels move with the main array, but are tilted from the plane of the array by equal but opposite angles. During our investigation we were not able to accurately determine the optimum angle - actual arctic field tests would be required to determine this - so we settled on an angle of 30° from the array plane (see figure 8).

The sensor panels are wired in a series loop, with the motor leads connected in parallel with the two panels. Thus the motor will receive no current when the output from the two panels is equal. When the output from one sensor panel is higher than the

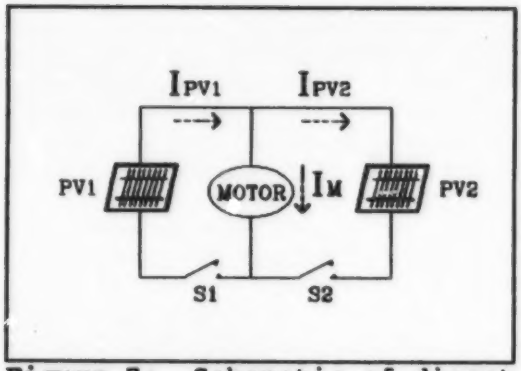

Figure 7: Schematic of direct drive tracker

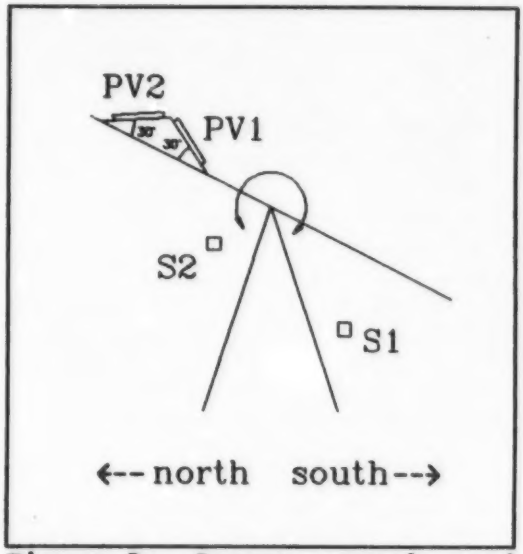

Figure 8: Sensor panel and limit switch orientation for direct drive tracker

other, the motor current will equal the difference between the two panels, and the motor will move the array toward the high output sensor, until the two sensor panels again have a balanced output.

In order for this type of controller to work properly as a direct drive system, the operating characteristics of the sensor panels must be properly designed to match the operating characteristics of the motor. In particular, the motor must be able to start when the difference in irradiance levels falling on the two sensor panels is relatively small. For the motor/gearbox we used in the prototype, the power required to start the motor under no load was 0.67 A @ 0.73 volts. The power required to start the motor when it is under load increases with load; under moderate loading the motor required 0.94 A @ 0.94 volts to start, and it could be stalled from heavy loading up to approximately 1.3 volts. By using a circuit of 3 series-connected solar cells, we achieve an operating voltage of 1.3 to 1.5 volts, in a range where the motor will not normally stall.

Having determined the number of cells in series to produce a correct operating voltage, the number of parallel strings of cells required to produce the proper operating current must be determined. The motor requires only about 0.55 A to operate at 1.0-1.5 volts, with up to approximately 1.0 A to start under the load of the tracker, a current which can easily be supplied by half of a standard 100 mm x 100 mm solar cell. However, the motor only receives the net difference in current output of the two sensor panels. Normally we would want the tracker to start when the irradiance level on the "bright" sensor panel is approximately 50 W/m^2 brighter than that falling on the array in its present position. Under typical sky conditions, this would imply that the

irradiance level on the "dim" sensor panel would be more than 100 W/m^2 below that of the "bright" panel. As an example, we will select the size of sensor panel required to begin turning the array when the difference in irradiance levels between the two sensor panels is 150 W/m^2.

At 150 W/m^2, the current from one of our standard solar cells is approximately 0.4 amps (at a typical operating voltage). Because the output current of a solar cell varies essentially linearly with irradiance, this would be the net current to the motor when the difference in irradiance levels was 150 W/m^2, independent of the actual irradiance levels (e.g. they could be 900 and 750 W/m^2 or 475 and 325 W/m^2). As we require approximately 1 A to start the tracker, we require 2.5 cells in parallel to produce this current. In fact, we chose to use 3 cells in parallel, which would produce the 1 amp starting current at an irradiance differential of apprximately 125 W/m^2, providing a slightly higher sensitivity. After starting, the motor continues to drive the tracker until the drive current falls to approximately 0.55 A, which corresponds to an irradiance differential of 69 W/m^2. Under typical sky conditions, this would imply that the irradiance on the plane of the array would be about 25 - 30 W/m^2 below the maximum.

Naturally, sensitivity can be increased by using sensor panels with greater output currents, but this also increases the cost. For the prototype we chose to use two 9-cell panels, each wired with three parallel strings of 3 cells each. Use of an upright shading plate between the two sensor modules would also increase sensitivity, possibly allowing for the use of smaller panels.

3.2 Evaluation of Prototype Trackers

Both trackers were tested for proper operation in controlled, indoor conditions, and outdoors. However, neither prototype was subjected to rigorous testing in terms of tracking accuracy, reliability, etc. Rather, they were evaluated in a qualitative manner only. Even such quantitative items such as cost are only approximate; accurate pricing can only be done when the product is being prepared for production in specific quantities.

Both trackers operated as intended. Overall, we felt more comfortable with the direct drive controller. In the section below, the two prototypes are compared against each other in several categories.

Cost: Both trackers share the cost of the motor with mounting hardware and crank arm. Based on our parts and labour cost, and using standard pricing policy, this part of the tracker would sell for about $240. The selling price of the electronics package and irradiance sensors (c/w mounting arm and limit switches) for the

2-station tracker would be approximately $380, for a total cost of the tracker of $620.

In contrast, the selling price of the two 9-cell sensor panels required for the direct drive unit, complete with mounting hardware and limit switches, is estimated at $260, for a total tracker price of $500, 81% of the price of the 2-station controller.

Ease of Use: The direct drive tracker is not intended to be adjustable, and thus requires no special set up. The two stations on the two station tracker must be set properly for location and time of year. As this requires little effort, there is no significant difference in the ease with which each system can be used.

If the system is in use for several weeks, the sesnors on the two-station controller can be adjusted to optimum values each month. For this minimal additional effort, the user should be able to produce more energy.

Reliability: The direct drive system is considered to be much more reliable than the 2-station tracker. The reliability of the motor (which is common to both trackers) cannot be accurately measured in short term tests on a prototype, but it should be quite high considering the motor was designed for outdoor use, and that we are operating it well below the design operating point.

The two sensor panels will be very reliable; PV power modules of similar design have a demonstrated failure rate from all causes of 0.013%/year. The limit switches are selected for their ruggedness, and should not be a significant problem, even though they may be the least reliable component in the tracker.

In contrast, the electronic logic of the 2-station tracker, while simple electronics, does consist of many small components which could fail. Also, the need to mount the sensor cells on long arms which reach outside of the swing of the array (to avoid shading) introduces a risk that they could be broken or bent accidentally. (Indeed, we broke one sensor when moving the structure during tests.) Thus the direct drive system is considered to be much more reliable.

Effectiveness: The effectiveness of the tracker relates to to its abillity to accurately point the array in the direction of the highest irradiance, **when it is operating properly** (i.e., excluding when it is broken or improperly set up). This parameter is very difficult to measure, even in a long term field test, so our evaluation of the effectiveness of the two trackers is very coarse.

The 2-station tracker should always move the array to the station which has the greatest irradiance incident on it; thus the only limitation to its effectiveness is that the brightest area of the sky will not normally be lined up directly with one of the predefined stations. In our earlier analysis of the weather data we concluded that this was not a serious limitation for northern sites (refer to figures 2 & 4).

The direct drive tracker is not limited to predefined stations, but has other limits to its effectiveness. Because of the inherent characteristics of this tracker, it will tend to lag behind the sun as it moves through the sky, thus receiving less than the maximum available irradiance at most times. Also, this type of tracker is susceptible to getting "lost". This can happen when the two sensor panels are receiving the same irradiance level, but are actually pointed toward equally dull areas of the sky, rather than equally bright areas of the sky. Each incident of this type could result in the array pointing in the wrong direction for a period of from a few minutes to several hours. To help prevent the array from getting "lost", we would modify the array crank arm to restrict the field of movement of the array to that area of the sky which is most likely to be the brightest, i.e. from an 80° south-facing tilt to a 30° north-facing tilt. This modification itself introduces a limit on the tracking effectiveness when the sun is at a low angle to the north.

Without substantial field testing, we cannot determine which tracker would be most effective, but based on the factors discussed above, we believe that the two would be comparable. That is, two identical arrays located side-by-side but equipped with the different trackers would have the same gross electrical output over a season of operation. (N.B. In evaluating the performance of these two trackers against the design goals -see section 4.2.1 - we have assumed that they are equally effective, and that they will produce a benefit equal to that of the 2-station tracker we used in our weather analysis.)

Parasitic Losses: The parasitic loss associated with a tracker is the amount of system energy used by the tracker in performing its job. By definition, the parasitic loss of the direct drive tracker is zero, because the power used to move the array is generated by the sensor panels, and is completely separate from the system power.

The energy consumption of the 2-station tracker is estimated at 20.7 Wh/day, drawn from the main storage battery. As shown in the sample calculation on page 13, this is not a problem when the tracker is installed on an array with several modules, but may become a problem when the number of modules is low (1-3).

There is also a small potential for the parasitic losses to increase substantially if a fault condition should occur which would cause the controller to draw a higher current. Gross increases can be avoided by proper fusing.

4 Structure Design

During this project, AstroPower personnel discussed many ideas for structures, reduced various ideas to conceptual designs, and eventually we designed and fabricated two different prototypes. The conceptual designs were discussed in our third progress report. This section deals with the structural components of the two prototype designs which were actually built as part of this project.

4.1 Tripod Mount

The tripod mount concept was selected for prototyping because of its high portability. A drawing of the assembled structure (not including the PV modules) is shown in figure 9. General specifications for the unit are given in figure 10.

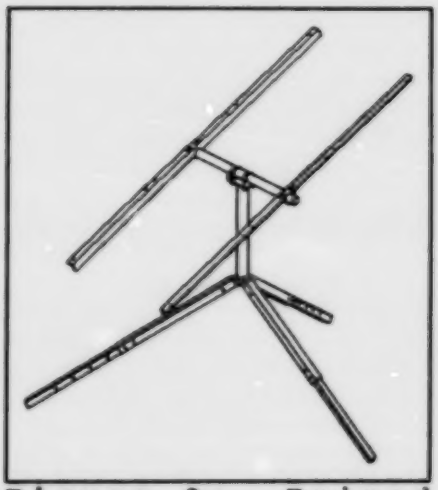

Figure 9: Tripod Mounting Structure

While this tripod is highly portable, it is useful only where relatively small amounts of power are required; it is designed to support a small array of 100 - 300 Wp, and it incorporates no tracking capability to boost its output. Its primary use would probably be with travelling expeditions which change camp sites every few days, and sites where access is by foot or small vehicles such as a snowmobile.

It is capable of supporting both our standard, glass-faced PV modules, or our light weight MP modules with a clear plastic film face. Naturally the system becomes more portable with the lightweight modules. The prototype we built was equipped with three standard glass modules.

In field use, the user will need to be careful of the array in high winds. While the structure itself is designed to withstand wind speeds of 80 km/hr, the anchoring pegs may get pulled from the ground with lesser winds, depending upon soil conditions.

4.1.1 Achievement of Design Goals

Tripod Mount Specifications

Material:	Anodized aluminum Stainless steel hardware Steel anchoring pegs
Modules:	Up to 3 standard APC5044 50 Wp modules (glass front) Up to 6 MP45 45 Wp modules (plastic film front)
Tracking:	None
Weight:	Structure (c/w bolts, pegs, etc.): 5.5 kg 3 APC5044 modules (c/w bolts & cables): 19.5 kg 6 MP45 modules (c/w bolts & cables): 23.0 kg
Packed Size:	Structure fits in 135 cm x 8 cm dia. bag: 0.007 m^3 3 APC5044 modules fit in a 98 x 46 x 17 cm package: 0.077 m^3 6 MP45 modules fit in a 118 x 66 x 3 cm package: 0.023 m^3 (The cable harness can fit in the bag with the structural components.)
Max. Wind Load:	80 km/hr on structure. Anchor pegs may release at lower wind speed, depending upon ground conditions.
Retail Cost:	$ 420 (excluding modules)
Assembly Time:	Setup will take approximately 0.5 - 2 hours for 1 person, depending upon the number of modules on the array, the experience of the person, and the weather. Disassembly will take approximately half of the setup time.

Figure 10: Tripod Mount Specifications

When this project was proposed, six design goals were developed (refer back to table 1). In this section, the tripod mount design is reviewed against each of these design goals.

The first design goal related to the setup and take down time of the array. The stated design goal was to limit each of these activities to under 4 hours for a two man team, dressed in winter clothing. This goal is too high for this particular design, which was specifically selected as being suitable for very short term camps. The setup procedure for the prototype with three standard modules consists of fastening 26 bolts/nuts, including adjusting the leg lengths to provide a level mount, driving a peg through each of the three legs to anchor the structure, and then wiring the modules together (by tightening two screws per module). We estimate that this would not take one person more than an hour. Disassembly would probably be even faster. This would seem to be a reasonable level of effort for a system which could be moved as often as every day.

The second design goal related to the size (when packed) and weight of the array. With three of our standard APC5044 modules, the array will weigh 0.19 kg/Wp, below the maximum target of 0.25 kg/Wp. If we were to use six lightweight MP modules, the weight

of the total array would be about 0.09 kg/Wp, well below the design goal.

The cost goal for this structure was also easily achieved. Based on material and labour costs, with normal markups, the retail price of this structure, including FST, would be approximately $420.

The fourth design goal related to the cost vs. performance of the tracking system, which is not applicable to this structure.

Our goal in terms of packaging was to not have any detachable packaging material which could get lost. We did not achieve this goal; when faced with the actual components of the design, we decided that it would be best to carry the structural components in a nylon bag, similar to a tent bag. Even if lost this could be readily replaced. The modules would be carried in a separate bag or carton.

We believe that this system would have no difficulty in meeting the design life of 10 years. While this is difficult to prove, the structural components are simple, use rugged hardware, and are designed for significantly higher stresses than they are expected to be subjected to.

4.2 Flipover Mount

Our second prototype, termed a flipover mount, holds a larger number of PV modules, supporting an array of up to 800 Wp. As suggested by its name, this structure does incorporate tracking capability. A drawing of the structure is shown in figure 11. The modules are mounted in a line along the length of the structure; the longitudinal beams of the structure can telescope to adjust for different numbers of modules. (Or fixed length pieces can be supplied at slightly lower cost.) General specifications for the structure are given in figure 12.

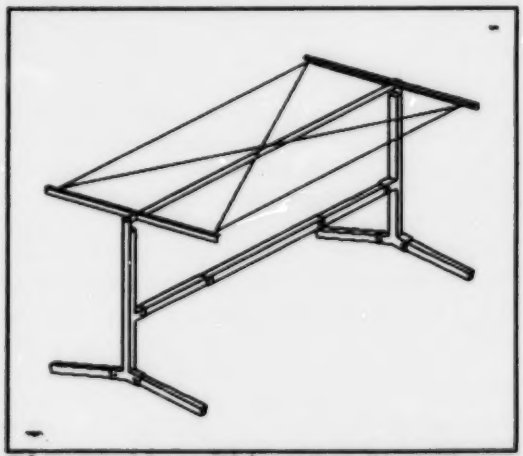

Figure 11: Flipover Structure

As with the tripod mount, either standard modules or light weight MP modules can be used. In larger sizes, where the weight of the structure itself (which is steel, not aluminum) and accompanying batteries is great, the standard glass modules would be preferred because of their greater ruggedness. However, the MP series do offer a significant advantage, in that they can be

Flipover Mount Specifications

Material: Painted Steel
Stainless steel hardware
Steel anchoring pegs

Modules: Up to 15 standard APC5044 50 Wp modules (glass front)
Up to 20 MP45 45 Wp modules (plastic film front)
(This structure can be made in various sizes (lengths). The number of modules given here are judged to be the maximum number for a unit which remains transportable.)

Tracking: 2-station flipover tracking, direct drive controller.

Weight:

Structure (c/w bolts, pegs, tracker, etc.):	65 kg
6 APC5044 modules (c/w bolts & cables):	38 kg
8 modified MP45 modules, in a folding module plate:	35 kg

Packed Size:

Structure fits in 1.5 m x 20 cm dia. bag:	0.047 m^3
plus 4 2.5 m lengths of steel:	0.016 m^3
6 APC5044 modules fit in a 98 x 46 x 34 cm package:	0.153 m^3
8 MP45 modules, w\folding module plate, fit in a 118 x 66 x 6 cm package:	0.047 m^3

(The cable harness can fit in the bag with the structural components.)

Max. Wind Load: 100 km/hr on structure. Anchor pegs may release at lower wind speed, depending upon ground conditions.

Retail Cost: $ 1,000, fixed tilt (excluding modules)
$ 1,500, w/tracker (excluding modules)

Assembly Time: Setup will take approximately 1 - 3 hours for 2 persons, with a folding module plate, depending upon the number of modules on the array, the experience of the person, and the weather. With 6 standard modules, set up would take 2 - 4 hours for 2 persons. Disassembly will take approximately two thirds of the setup time.

Figure 12: Flipover Mount Specifications

made longer and narrower. This results in a 33% increase in the amount of output power per linear foot of the structure. (In theory, the same design change can be made in our glass modules, but the high cost of small orders of custom sizes of tempered glass and frame parts makes the change impractical.)

The key to making this array transportable was the development of the folding module plate concept. The folding module plate consists of an even number of modules which are a slight variation on our MP45 module, which are then fastened together with hinges (see figure 13). These modules are lightweight and readily fold into a rugged, compact package for transport. Setup would involve unfolding the modules, and attaching them to the structure with several bolts. Primarily because of the high costs of solar cells this unit was not prototyped, thus we have not fully answered such questions as to whether or not we can effectively use captive bolts, and whether or not the folding modules can remain wired together in their folded state. As we have not been able to fully

answer these questions, we have assumed the worst case (e.g. wiring harness which must be detached and reattached when the array is moved) when evaluating this unit against the design goals.

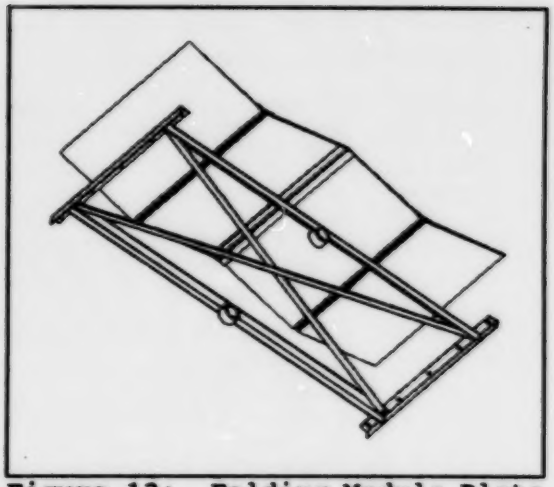

Figure 13: Folding Module Plate for 4 Modules

Because this design is flexible in terms of the number and type of modules used, and whether or not tracking is employed, it was necessary to select a specific configuration to use in evaluating against the design goals. In order to ensure reasonable accuracy in our evaluation, and because it represents what we feel would be a typical size, we chose a configuration essentially the same as the one we prototyped. It consists of a structure that can hold an array 2.75 m long (6 standard modules for 300 Wp or 8 MP-type modules for 400 Wp), with the direct drive tracking. When evaluating the structure with MP-type modules, a folding module plate is assumed, rather than individual modules.

4.2.1 Achievement of Design Goals

For the purposes of evaluating the achievement of design goals, a tracking array (using the direct drive tracker) of either 6 standard modules or 8 modified MP modules in a folding module plate will be used (see specifications in figure 12).

The setup time of this array is estimated to be 1-3 hours for a two man team, when a folding array plate is used. This is well under the design goal of 4 hours. If standard modules were used which had to be individually mounted and wired, the setup time would probably be in the order of 3-6 hours, depending upon the weather and the skill of the people. Disassembly and packing would require about 2/3's of the time required to set up the array. Increasing the number of modules would not significantly affect the setup time for an array with a folding module plate.

The weight-to-power ratio for this design is 0.34 kg/Wp using standard modules, and 0.25 kg/Wp with the lighter weight modules. As the design goal was 0.25 kg/Wp, this design meets the goal only if the folding module plate is used. Structures for larger modules would have a lower kg/Wp ratio. Also, the weight of the array could be lowered to approximately 40% of that shown by making it out of aluminum, but the price would be double that of the steel

structure. The sizes of the components are such that they can readily be transported by small aircraft, meeting this design goal.

The retail cost of a fixed tilt structure, complete with folding module plate hardware (but not the actual modules), is estimated at only $1,000, or equivalent to the cost of 2 modules. This is only 0.33 times the cost of six modules alone, well below the design goal of 1.0.

The cost of adding the tracking is estimated at $500 (motor, direct drive sensor/power modules, structure modifications). If we assume that the tracking increases the power output by 20% over a fixed array of six modules (see figure ???), then the enhanced performance due to the tracker is equivalent to adding 1.2 modules. The cost of 1.2 modules is $600; 80% of this cost is $480, slightly below the $500 cost of the tracker. On this basis, the design goal is not quite met, however, if we had assumed the 8 module folding plate, or slightly better than a 20% increase in performance due to tracking, the design goal is met. (Because the actual benefit of tracking is highly site dependent, the cost/performance benefit of tracking must be determined on an individual basis.)

As with the smaller tripod structure, we did not achieve our goal of having all packaging elements permanently attached to the structure. Although this is probably feasible, we felt the cost penalty would be too great. We chose to package the structure in two canvass bags - one for most of the structural pieces, and a second one for the modules. In addition, there would be four 2.5 m lengths of steel tubing and angle which would be carried individually, with no packaging (it was decided to exclude these from the bag in order to reduce its length - to about 1.5 m - and to keep its weight readily manageable at about 45 kg).

We believe that there will be little difficulty in achieving a 10 year life for this system. It may require occasional touch up paint. There is a also reasonable potential for module breakage during 10 years of handling, but this would only require the replacement of the affected module(s), if it were to occur.

5 Conclusions

AstroPower designed and prototyped two structures which are suitable for use in temporary field camps, in the Canadian north or elsewhere, including one which incorporates a sun tracking capability. Both structures essentially met the design goals set for the project. As the units were only brought to the prototype stage during this project, finishing touches are missing; these should be added.

One PV array is particularly suitable for mobile field camps which require very small amounts of electrical power, while the

other is better suited to camps which will remain in place for two weeks or longer, but can supply significantly more power.

Flipover tracking, the rotation of the array around a horizontal east-west axis, can be effectively implemented for sites north of the arctic circle. Below this latitude the benefits are not such that they justify the cost.

Appendix A

Weather Data for Seven Northern Sites

Resolute, 1986
Insolation data in peak sun hours per day.

MONTH	90 S	75 S	60 S	45 S	30 S	15 S	0	15 N	30 N	45 N	60 N	75 N	90 N	Flipover	2-axis
January	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
February	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.69	0.76
March	5.34	5.51	5.31	4.77	3.94	2.87	1.67	0.58	0.48	0.56	0.65	0.72	0.77	5.53	7.52
April	7.13	7.70	7.83	7.50	6.78	5.70	4.42	3.08	2.03	2.04	2.23	2.42	2.52	8.91	13.68
May	5.20	5.86	6.24	6.38	6.25	5.89	5.44	4.91	4.22	3.85	3.89	3.91	3.81	8.00	10.59
June	4.53	5.16	5.61	5.83	5.84	5.65	5.45	5.12	4.65	4.18	4.14	4.05	3.84	7.50	9.15
July	2.72	3.20	3.58	3.84	3.91	3.86	3.75	3.56	3.25	2.98	2.84	2.67	2.43	4.92	5.75
August	1.57	1.85	2.05	2.16	2.21	2.17	2.07	1.95	1.80	1.70	1.63	1.53	1.37	2.69	3.08
September	2.40	2.59	2.65	2.57	2.34	2.02	1.62	1.19	0.96	0.96	0.97	0.98	0.96	2.79	3.62
October	2.12	2.15	2.03	1.79	1.42	0.97	0.50	0.20	0.21	0.25	0.27	0.29	0.28	2.16	2.48
November	0.07	0.07	0.06	0.05	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.07
December	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Annual Avg.	2.59	2.84	2.95	2.91	2.73	2.43	2.08	1.72	1.47	1.38	1.38	1.38	1.34	3.60	4.72
Summer Avg.	4.89	5.48	5.81	5.89	5.70	5.28	4.76	4.17	3.54	3.26	3.27	3.26	3.15	7.33	9.79

Alert, 1986
Insolation data in peak sun hours per day.

MONTH	90 S	75 S	60 S	45 S	30 S	15 S	0	15 N	30 N	45 N	60 N	75 N	90 N	Flipover	2-axis
January	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
February	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
March	2.44	2.47	2.33	2.03	1.61	1.08	0.53	0.20	0.22	0.26	0.30	0.32	0.33	2.56	4.09
April	6.88	7.25	7.16	6.68	5.86	4.77	3.84	3.30	3.58	4.22	4.76	5.09	5.15	10.99	16.43
May	6.10	6.66	6.88	6.83	6.49	6.02	5.77	5.42	5.06	5.26	5.49	5.49	5.32	10.10	13.60
June	4.03	4.55	4.87	5.06	5.07	5.07	5.20	5.14	4.92	4.85	4.79	4.60	4.26	7.38	8.94
July	3.25	3.74	4.07	4.23	4.24	4.18	4.16	4.03	3.78	3.71	3.63	3.43	3.13	5.86	7.02
August	3.50	3.91	4.11	4.12	3.91	3.56	3.28	3.01	2.85	2.97	3.04	3.01	2.83	5.89	7.84
September	2.06	2.14	2.10	1.92	1.64	1.28	0.89	0.68	0.75	0.83	0.90	0.93	0.91	2.63	4.01
October	0.48	0.47	0.43	0.36	0.27	0.15	0.03	0.01	0.01	0.02	0.02	0.02	0.02	0.48	0.64
November	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
December	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Annual Avg.	2.40	2.60	2.66	2.60	2.42	2.18	1.98	1.82	1.76	1.84	1.91	1.91	1.83	3.82	5.21
Summer Avg.	5.07	5.55	5.75	5.70	5.42	5.01	4.74	4.47	4.33	4.51	4.67	4.65	4.46	8.58	11.50

Yellowknife, 1986
Insolation data in peak sun hours per day.

MONTH	90 S	75 S	60 S	45 S	30 S	15 S	0	15 N	30 N	45 N	60 N	75 N	90 N	Flipover	2-axis
January	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
February	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.51	0.53	3.42	3.97
March	4.56	4.89	4.95	4.70	4.20	3.49	2.61	1.62	0.98	1.00	1.08	1.16	1.20	5.01	6.31
April	6.41	7.25	7.69	7.69	7.28	6.49	5.38	4.03	2.54	1.65	1.69	1.84	1.96	8.01	11.44
May	3.74	4.51	5.10	5.46	5.59	5.44	5.09	4.49	3.72	2.86	2.48	2.31	2.12	6.96	8.04
June	3.63	4.47	5.16	5.64	5.94	5.97	5.78	5.36	4.73	3.94	3.35	3.04	2.75	6.76	8.74
July	4.10	5.02	5.80	6.29	6.55	6.50	6.18	5.60	4.80	3.82	3.19	2.92	2.71	7.33	9.74
August	3.32	3.99	4.47	4.74	4.78	4.59	4.22	3.63	2.95	2.26	2.02	1.91	1.76	5.04	6.54
September	3.27	3.71	3.96	3.98	3.75	3.34	2.74	2.05	1.33	1.11	1.09	1.06	1.02	4.08	5.36
October	1.18	1.28	1.32	1.30	1.20	1.04	0.85	0.65	0.56	0.54	0.53	0.51	0.47	1.38	1.55
November	1.85	1.88	1.78	1.58	1.27	0.90	0.47	0.22	0.22	0.25	0.27	0.29	0.28	1.89	2.07
December	0.84	0.83	0.76	0.65	0.48	0.29	0.09	0.04	0.04	0.05	0.05	0.06	0.05	0.84	0.89
Annual Avg.	2.74	3.15	3.42	3.50	3.42	3.17	2.78	2.31	1.82	1.46	1.31	1.30	1.24	4.15	5.39
Summer Avg.	4.47	5.31	5.94	6.27	6.34	6.10	5.61	4.87	3.95	3.07	2.68	2.53	2.38	7.04	9.49

Hall Beach, 1986
Insolation data in peak sun hours per day.

MONTH	90 S	75 S	60 S	45 S	30 S	15 S	0	15 N	30 N	45 N	60 N	75 N	90 N	Flipover	2-axis
January	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
February	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	0.30	2.54	2.83
March	5.51	5.80	5.71	5.27	4.51	3.50	2.33	1.10	0.71	0.78	0.89	1.00	1.06	5.83	7.62
April	6.92	7.67	7.97	7.84	7.28	6.34	5.13	3.72	2.28	1.86	1.97	2.10	2.24	8.47	12.67
May	4.69	5.34	5.81	6.02	6.01	5.76	5.35	4.78	4.20	3.66	3.33	3.32	3.25	7.11	9.49
June	4.60	5.39	5.97	6.34	6.49	6.40	6.18	5.89	5.36	4.70	4.48	4.37	4.19	8.36	10.71
July	3.56	4.28	4.87	5.23	5.39	5.31	5.12	4.81	4.34	3.74	3.50	3.32	3.09	6.77	8.65
August	2.39	2.82	3.14	3.31	3.34	3.21	2.96	2.62	2.22	1.91	1.80	1.69	1.54	3.71	4.59
September	1.97	2.19	2.29	2.30	2.18	1.96	1.68	1.36	1.13	1.07	1.04	1.01	0.94	2.40	2.86
October	2.23	2.30	2.24	2.02	1.70	1.27	0.88	0.62	0.41	0.43	0.46	0.48	0.47	2.34	2.67
November	0.75	0.75	0.70	0.61	0.46	0.29	0.11	0.05	0.06	0.07	0.07	0.07	0.07	0.76	0.80
December	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Annual Avg.	2.72	3.04	3.23	3.24	3.11	2.84	2.47	2.06	1.72	1.50	1.46	1.47	1.43	4.02	5.24
Summer Avg.	4.94	5.67	6.16	6.36	6.29	5.95	5.45	4.80	4.02	3.44	3.32	3.28	3.19	7.68	10.38

Inuvik, 1986
Insolation data in peak sun hours per day.

MONTH	90 S	75 S	60 S	45 S	30 S	15 S	0	15 N	30 N	45 N	60 N	75 N	90 N	Flipover	2-axis
January	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
February	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.21	1.44	1.60
March	5.20	5.46	5.37	4.96	4.24	3.28	2.16	1.00	0.63	0.68	0.78	0.87	0.91	5.50	7.05
April	6.22	6.85	7.11	6.96	6.41	5.55	4.42	3.11	1.78	1.42	1.52	1.64	1.76	7.48	10.98
May	3.92	4.55	4.98	5.17	5.16	4.93	4.54	4.00	3.34	2.73	2.61	2.53	2.45	6.11	8.12
June	4.75	5.77	6.54	7.02	7.19	7.09	6.77	6.31	5.57	4.64	4.32	4.14	3.90	9.43	12.61
July	3.17	3.83	4.36	4.71	4.89	4.88	4.70	4.43	3.98	3.43	3.16	2.96	2.71	5.99	7.62
August	2.51	2.96	3.31	3.49	3.53	3.41	3.16	2.80	2.36	2.03	1.89	1.77	1.61	3.79	4.65
September	3.08	3.44	3.61	3.56	3.30	2.87	2.30	1.65	1.07	1.00	0.99	0.98	0.93	3.72	4.92
October	1.23	1.31	1.29	1.22	1.06	0.88	0.65	0.44	0.42	0.42	0.41	0.40	0.38	1.35	1.53
November	0.91	0.91	0.84	0.72	0.53	0.33	0.11	0.05	0.05	0.06	0.07	0.07	0.06	0.92	0.96
December	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Annual Avg.	2.58	2.92	3.12	3.15	3.03	2.77	2.40	1.98	1.60	1.37	1.31	1.30	1.24	3.81	5.00
Summer Avg.	4.52	5.25	5.75	5.96	5.91	5.61	5.11	4.46	3.67	3.05	2.90	2.82	2.71	7.25	9.83

Whitehorse, 1986
Insolation data in peak sun hours per day.

MONTH	90 S	75 S	60 S	45 S	30 S	15 S	0	15 N	30 N	45 N	60 N	75 N	90 N	Flipover	2-axis
January	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
February	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.62	0.64	3.76	4.27
March	3.04	3.32	3.45	3.38	3.12	2.72	2.21	1.63	1.18	1.14	1.16	1.19	1.17	3.51	4.27
April	4.11	4.61	5.04	5.14	5.00	4.63	4.04	3.31	2.69	1.92	1.88	1.89	1.88	5.37	7.40
May	3.22	3.90	4.46	4.84	5.03	5.01	4.79	4.38	3.84	3.19	2.80	2.56	2.32	5.50	7.12
June	3.56	4.35	5.06	5.57	5.92	5.99	5.91	5.58	5.01	4.30	3.63	3.29	3.00	6.90	9.07
July	3.21	3.92	4.56	4.99	5.23	5.26	5.10	4.74	4.19	3.52	2.99	2.72	2.46	5.94	7.69
August	2.99	3.62	4.10	4.38	4.47	4.37	4.06	3.59	2.99	2.35	2.07	1.92	1.76	4.76	6.16
September	3.09	3.56	3.83	3.90	3.74	3.39	2.87	2.23	1.53	1.22	1.16	1.14	1.08	3.99	5.30
October	1.62	1.79	1.86	1.83	1.68	1.45	1.17	0.86	0.71	0.69	0.67	0.65	0.60	1.91	2.11
November	1.23	1.28	1.25	1.13	0.95	0.74	0.49	0.28	0.29	0.30	0.31	0.31	0.30	1.30	1.39
December	0.57	0.58	0.55	0.47	0.38	0.26	0.13	0.09	0.09	0.09	0.09	0.09	0.08	0.58	0.61
Annual Avg.	2.22	2.58	2.85	2.97	2.96	2.82	2.56	2.22	1.86	1.56	1.40	1.37	1.27	3.63	4.61
Summer Avg.	3.53	4.21	4.78	5.13	5.29	5.22	4.96	4.50	3.88	3.23	2.82	2.62	2.42	5.93	7.80

Iqaluit, 1986
Insolation data in peak sun hours per day.

MONTH	90 S	75 S	60 S	45 S	30 S	15 S	0	15 N	30 N	45 N	60 N	75 N	90 N	Flipover	2-axis
January	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
February	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.41	0.40	2.00	3.09
March	6.60	7.07	7.10	6.70	5.89	4.78	3.62	1.95	1.00	1.07	1.21	1.36	1.48	7.14	9.26
April	5.72	6.44	6.82	6.84	6.49	5.84	4.91	3.79	2.59	1.94	1.97	2.07	2.15	7.16	9.85
May	4.28	4.93	5.45	5.70	5.75	5.56	5.17	4.58	3.84	3.07	2.82	2.72	2.63	6.21	7.94
June	3.60	4.31	4.91	5.32	5.53	5.54	5.33	4.95	4.39	3.70	3.20	2.98	2.77	6.33	7.83
July	3.39	4.15	4.77	5.20	5.39	5.36	5.09	4.67	4.06	3.32	2.81	2.60	2.39	6.20	7.92
August	2.83	3.44	3.76	3.97	3.86	3.80	3.84	2.55	2.30	1.83	1.65	1.50	1.35	3.29	3.81
September	1.65	1.90	2.05	2.12	2.07	1.94	1.72	1.45	1.17	1.08	1.02	0.94	0.85	2.22	2.37
October	2.86	3.00	2.97	2.76	2.39	1.89	1.33	0.75	0.63	0.64	0.68	0.70	0.71	3.05	3.56
November	1.22	1.25	1.19	1.05	0.84	0.61	0.34	0.19	0.20	0.21	0.21	0.22	0.21	1.26	1.33
December	0.72	0.71	0.65	0.54	0.40	0.23	0.05	0.01	0.03	0.03	0.03	0.04	0.03	0.72	0.75
Annual Avg.	2.67	3.03	3.22	3.27	3.15	2.90	2.52	2.07	1.67	1.41	1.30	1.29	1.25	3.86	4.81
Summer Avg.	4.25	4.96	5.49	5.76	5.79	5.57	5.13	4.50	3.72	3.01	2.70	2.59	2.48	6.48	8.38